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Erosion Rate Investigation of Various Nozzle Materials in Hybrid Rocket Motors

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Thrust profile is very important for rocket motors. Nozzle design is a key parameter to predict thrust profile. Increase in nozzle throat area is very important for the system performance because I_{sp} changes when the throat area changes. Pressure decreases when throat area increases and this might cause a stability problem. Mechanical and chemical erosions can occur in nozzle throat. Due to high oxidizing agents in oxidizers of hybrid rocket motors and combustion products of fuel and oxidizer, chemical erosion can be seen in hybrid rocket motor nozzles. Consequently, operating at low O/F ratios can decrease erosion rate of nozzle throat due to low oxidizing agents. Additionally, higher chamber pressure means higher erosion rates due to increase in mass fluxes and heat transfer at nozzle throat. Fuel formulation also plays an important role in reducing nozzle erosion. Metal additives such as Al and Mg significantly reduce nozzle erosion since Al2O3 formation decreases the mass fraction of oxidizing agents. The most important thing that decreases nozzle erosion is the selection of nozzle material. Different graphite types and molybdenum tested as nozzle material for this study.

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Nomenclature

a = Regression rate coefficient
a_n = Nozzle regression rate coef
A_p = Fuel port area
A_n = Nozzle area
I_{sp} = Specific impulse
$\dot{m}_{ox}$ = Oxidizer mass flow rate
$\dot{r}$ = Regression rate
$\dot{r}_n$ = Nozzle regression rate
A_{nt} = Nozzle throat area
c^* = Characteristic velocity
C_d = Discharge coefficient
G = Local mass flux
n = Flux exponent
O/F = Oxidizer to fuel ratio
P_c = Chamber pressure
η_c = Combustion efficiency
t_b = Burn time

I. Introduction

In hybrid rocket motors, fuel and oxidizer are physically separated and one of the two is in liquid phase. In most cases, oxidizer is in liquid or gas form. Most of the hybrid rocket propulsion systems generate thrust by burning liquid oxidizer and solid fuel. Hybrid rocket motors gives a specific impulse (I_{sp}) between solid rocket propulsion systems and liquid rocket propulsion systems. Also, system complexity is slightly more than solid rocket motors and less than liquid rocket motors. Restart capability and throttling are some advantages of hybrid rocket motors compared to solid rocket motors. Since hybrid rocket motors reduce chemical explosion hazard due to the seperation of fuel and oxidizer, safety is another advantage of them. Furthermore, reduced development and management costs of hybrid rocket motors are very important advantages of them.

Wax and Polymers such as thermoplastics (Polyethylene, Plexiglas) and HTPB (Hydroxyl-terminated polybutadiene) are commonly used as solid fuels for hybrid rocket engines. Liquid nitrous oxide, liquid oxygen, and gaseous oxygen are generally used as an oxidizer in a hybrid rocket motor. Since LOX is a cryogenic oxidizer, it is not easy to handle. Moreover, nitrous oxide and gas oxygen can be used when Isp performance is not critical since LOX gives better I_{sp} than N_2O and GOX. In spite of a lot of advantages of hybrid rocket motors, they have a significant shortcoming which is low regression rate. Paraffin-based fuels gives higher regression rates at similar mass fluxes compared to polymer-based fuels due to liquefying theory of paraffin-based fuels[1] .Therefore, combination of paraffin wax and oxygen gives better performance in terms of regression rate.

In hybrid rocket propulsion systems the oxidizer is injected into a port in the solid fuel grain and the fuel grain melts under the flame. For this reason, a liquid layer forms on burning surface of the solid fuel. High gas velocities in the port cause liquid layer instabilities, so droplet formation occurs and mass transfer results in entrainment of liquid droplets from the melt layer.[1] These liquefying propellants increase the regression rate. Considerable amount of study in liqiud layer hybrid combustion theory can be seen in Ref. 1. Regression rate of hybrid rocket motor can be calculated using *Eq. 1*[2] where a is regression rate coefficient, n is mass flux exponent, and G is local mass flux in the port.

$$\dot{r} = aG^n x^m \tag{1}$$

Mass flux in the port can be defined as

$$G = \frac{\dot{m_{ox}}}{A_p} \tag{2}$$

In addition to the performance parameters (I_{sp}, regression rate) which are discussed above, thrust profile is also an important parameter in rocket propulsion systems. Nozzle design is a key parameter to predict thrust profile. Since reduction of nozzle area ratio causes I_{sp} loss, the variation of nozzle area ratio affects the thrust of the rocket engine. Mechanical and chemical erosions in nozzle throat can cause changings in rocket nozzle area ratio. Temperatures at the nozzle throat due to the combustion at high temperature and pressure can be considerably high and reach 3000-3500 K. Due to high mass fractions of oxidizing agents in hybrid and liquid rocket motors, chemical erosion is much more than solid rocket motors. Propellant combinations should not contain more than acceptable amount of free oxygen due to their high reactiveness at high temperatures. Therefore, O/F ratio plays an important role in nozzle erosion of liquid and hybrid rocket motors and running at low oxidizer to fuel ratios can decrease nozzle erosion rates. In addition, chamber pressure is one of the important parameters for nozzle erosion. Operating at low chamber pressures can be a good choice since high chamber pressures increase nozzle mass flux and heat transfer therefore, this speeds up nozzle erosion. Another option for minimizing nozzle erosion can be formulating fuels by reducing mass fractions of oxidizing species. For example, metal additives to the hybrid rocket fuels such as aluminum (AL), magnesium (Mg), ammonium borane (BH_3NH_3) or lithium aluminum hydride ($LiALH_4$) can decrease nozzle erosion rate.[3] The most important factor that minimizes nozzle erosion is the selection of suitable nozzle material. Materials that have been used in hybrid rocket propulsion systems can be determined in different groups[4]:

1) Carbon-based materials (Graphite, C-C composite)
2) Metals (Tungsten, tantalum, molybdenum, rhenium)
3) Ceramics (Silicon Carbide, Hafnium Carbide, Tungsten Carbide)
4) Polymer composites (Silica glass, carbon fibers)

In carbon-based materials, graphite is a better material for hybrid rocket motors, due to its better durability (with respect to C-C composites) for oxygen attacks. On the other hand, C-C increases mechanical strength of the nozzle. Therefore, it is more suitable for solid rocket motors since solid rocket motors are exposed to solid particle attacks.

Metals can be used due to their low chemical reaction possibility and high resistance to mechanical impacts and heat. Machinability of metals such as tungsten and tantalum is not easy thus they are not preferred much. Since ceramics are resistant to high temperatures, they can be preferred as nozzle material. They are not very common due to the difficulty of the production process and sometimes cost effectiveness.

Nozzle erosion rate can be written as,

$$\dot{r}_n = a_n(O/F)\, G_n^m \tag{3}$$

Where local mass flux is;

$$G_n = \frac{\dot{m}_p}{A_n} \tag{4}$$

By using c* equation, local flux can be written as

$$G_n = \frac{P_c C_d}{c^*_{theo}\eta_c} \frac{A_{nt}}{A_n} \tag{5}$$

Combining *Eq. 3* and *Eq. 5*, regression rate of nozzle throat [5] can be written as

$$\dot{r}_n = a_n(O/F)\left(\frac{C_d}{c^*_{theo}\eta_c}\right)^m \left(\frac{A_{nt}}{A_n}\right)^m P_c^m \tag{6}$$

Each material have an a_n coefficient which can vary with O/F.

A prominent factor to predict the nozzle erosion rate for specific materials is a_n coefficient. From tests which have same chamber pressures and different O/F ratios, a_n can be predicted by using *Eq. 10 [5]*. Experimental data is taken as reference and a_n coefficient is calculated by making linear erosion assumption for the nozzle material. After obtaining a_n, erosion prediction for the next tests can be made by using CEA.

$$(\dot{r}_n)_{ref} = \alpha_n \left(\frac{C_d}{c^{*}\eta}\right)^m P_{cref}^m \tag{10}$$

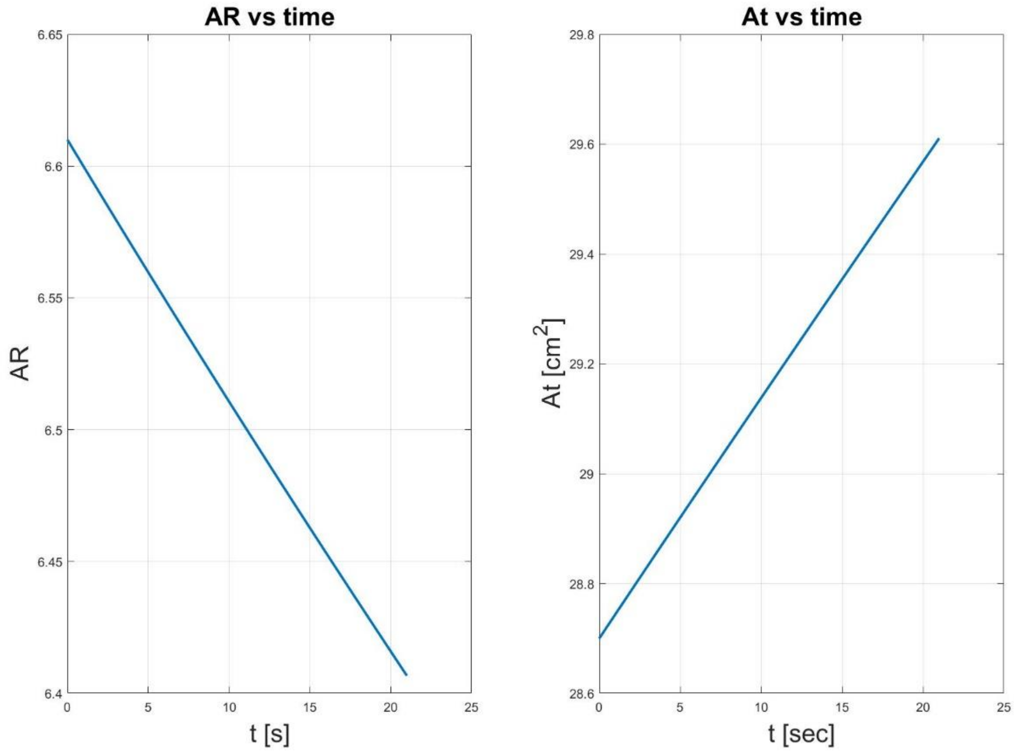

Figure 1: Area Ratio Prediction for Grade 1 Graphite Nozzle by Using CEA and Matlab.

In *Figure 1*, prediction of a test in matlab is shown. From experimental data AR reduces from 6.62 to 6.39 and in matlab it reduces from 6.62 to nearly 6.42. From matlab area ratio decrease is similar to the experimental one, so predictions and test results were very close to each other.

Nozzle erosion rate can be calculated by using *Eq (6)* if no test have been performed yet. However, if the material tested there is one more method to calculate erosion rate. Since the initial and final diameters of the nozzle throat are known, the erosion rate can be found from division of the difference between diameters by two times of difference between burn time and erosion onset. This calculation can be seen in *Eq.9.*

$$\bar{\dot{r}} = \frac{D_i - D_f}{2t_b} \tag{7}$$

$$\overline{G_o} = \frac{16\dot{m}_o}{\pi\left(D_i + D_f\right)^2} \tag{8}$$

$$\bar{\dot{r}}_n = \frac{D_{t_f} - D_{t_i}}{2(t_{burn} - t_{erosion\ onset})} \tag{9}$$

II. Experimental Setup and Tests

The focus of this study is determining throat erosion rates of different nozzle materials such as various types of graphite and molybdenum. In addition, development process of Silica Phenolic and Silicon Carbide continues. A lab scale hybrid rocket engine test setup which has 65 mm outer grain diameter and gaseous oxygen (GOX) as oxidizer is used for this study. Motor design can be seen in *Figure 1* and the test setup to determine nozzle throat erosion rates in hybrid rocket motor can be seen in *Figure 2*.

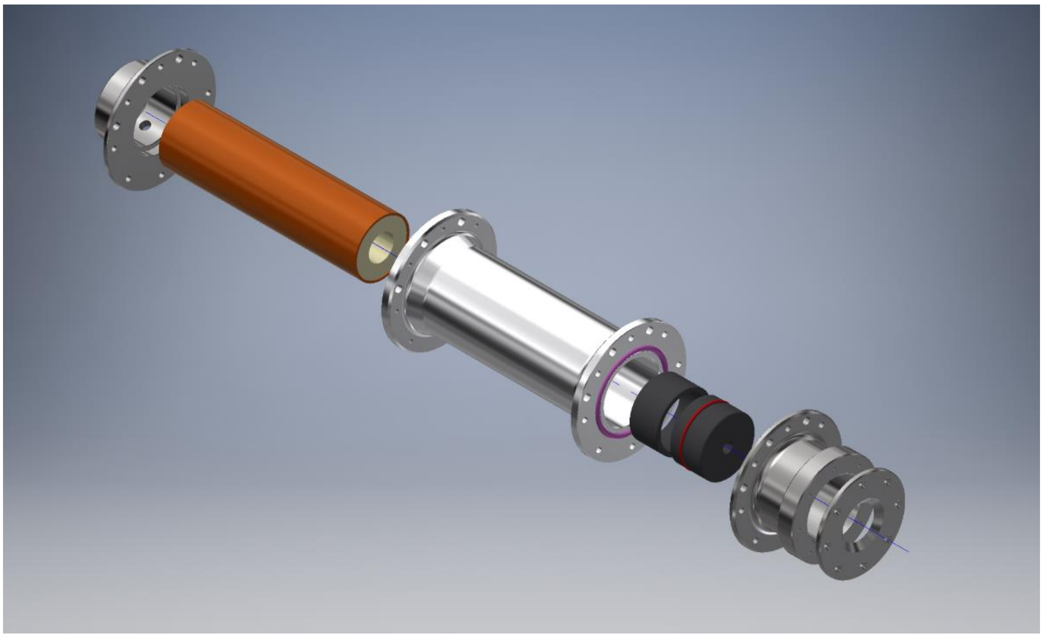

Figure 2: 65mm Grain Outer Diameter Hybrid Rocket Motor Design

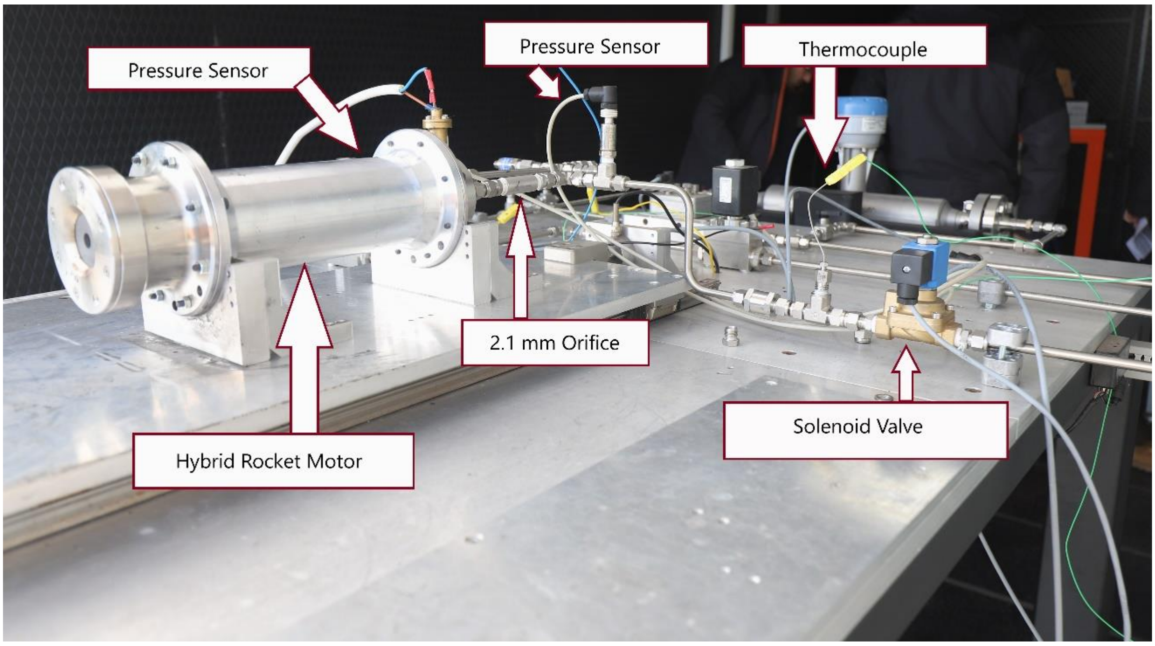

Figure 3: 65mm Grain Outer Diameter Hybrid Rocket Motor Test Setup

In the motor design, calculations were made by using CEA (NASA Chemical Equilibrium with Applications). System performance parameters (Regression rate, I_{sp}, O/F, c*, etc.) were taken from CEA and port diameters &lengths were calculated by using these data. Since O/F ratio and chamber pressure are the most important parameters for nozzle erosion, different grain lengths and different mass flow rates were used to change the O/F ratio. In addition to this, by changing tank pressure (same as pressure just before the orifice), with a regulator chamber pressure were changed as well.

In the test setup, 2,1 mm orifice and 3/8 in pipe entrance is used for GOX injection. Pressures are measured by using two different pressure sensors which are located before the orifice and in the pre-combustion chamber. Furthermore, a load cell system is used to measure the thrust.

First erosion tests have been started with different graphite grades. Graphite types and properties which are used for nozzle erosion tests are listed in *Table 1*. Ash content, porosity, grain size, thermal conductivity and coefficient of thermal expansion are very important for selection of graphite grade. Smaller grain size means lower erosion rates because graphites with small grain size are better sintered thus their porosities are less than others.

Graphite Type	**Grain Size**	**Porosity**	**Ash Content**	**Coefficient of Thermal Expansion (400-500°C)**	**Thermal Conductivity**	**Density**
Grade 1	8 µm	7%	300 ppm	6,0 x10E-6/°C	105 W/m°C	1,84 g/cm^3
Grade 2	9 µm	8%	300 ppm	5,6 x10E-6/°C	106 W/m°C	1,83 g/cm^3
Grade 3	13 µm	12%	300 ppm	5,2 x10E-6/°C	95 W/m°C	1,79 g/cm^3
Grade 4	15 µm	9%	750 ppm	4,3 x10E-6/°C	85 W/m°C	1,77 g/cm^3
Grade 5	4 µm	-	400 ppm	7,5 x10E-6/°C	120 W/m°C	1,88 g/cm^3

Table 1: Graphite Grade Types and Properties

In the erosion tests, grain outer diameter is 65 mm, but lengths are changed as mentioned before. Three different lengths such as 200mm, 250mm, 300mm are used to determine different oxidizer to fuel ratios. Besides, paraffin-based fuel formulation is named as DY12.

Grain inner and outer diameters, length, and weight are measured before and after tests to obtain data for the calculation of regression rate. In addition, nozzle throat diameter is also measured before and after the tests to obtain nozzle erosion rates. Measuring nozzle throat diameter manually by using t-scope is a good option. Moreover, photos of nozzles after tests were taken to use in a Matlab code which is written by using image processing toolbox and this code was used to determine the area change of the nozzle throat.

Some other tests performed at different scales (different from 65mm grain test setup) by using graphite Grade 1. A sample nozzle initial photograph is shown in *Figure 3*. After the test which has 14 bar average chamber pressure and 4 O/F ratio, nozzle erosion was too high because of higher O/F & longer burn time. Final shape of the nozzle is also shown in *Figure 4*.

Nozzle throat diameter increased by 48 % at the end of the test if it is calculated from image processing. Increase in nozzle throat diameter is 46.6% if it is measured manually. When manual measurement and image processing results are compared, it is clearly seen that they are very close to each other.

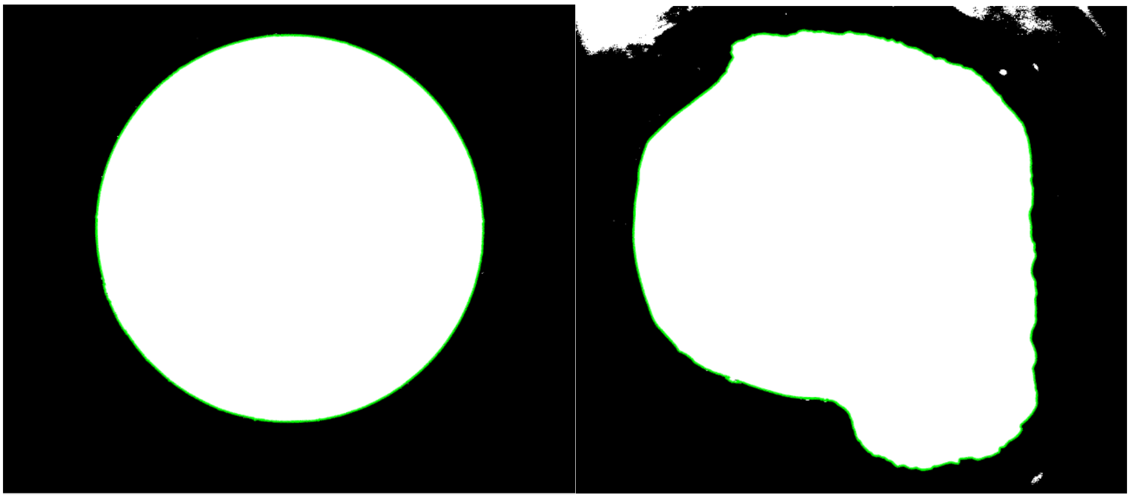

Figure 4: Grade 1 Nozzle Throat Erosion Photos Before&After the Test which were determined by Using Image Processing (14 Bar Pressure, O/F = 4)

Figure 5 shows the test which was performed by using the test setup and Grade 1 for nozzle material. In the test, chamber pressure and O/F ratio were 25 bar and 2.7. Nozzle diameter increased by 21% at the end of the test.

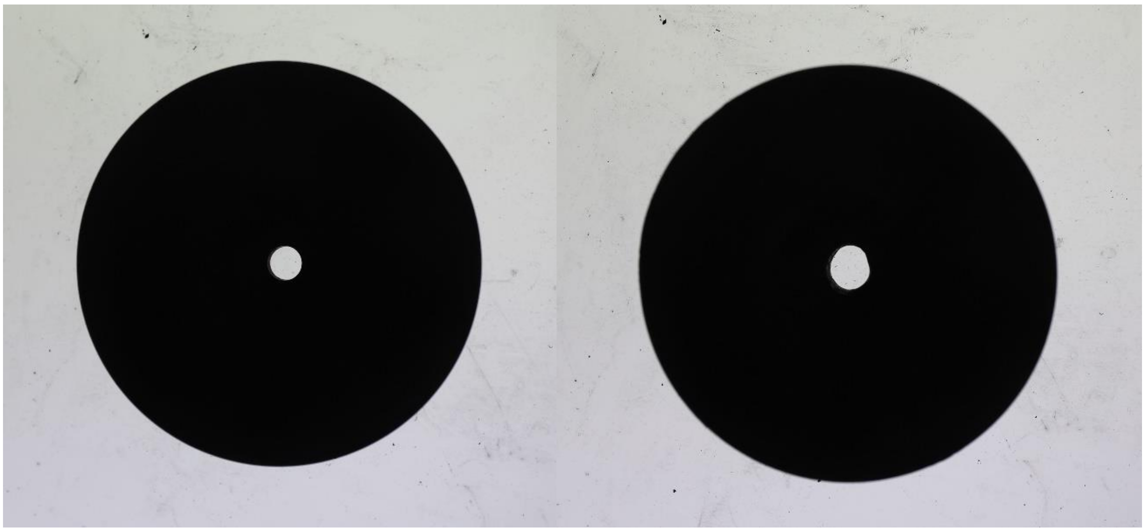

Figure 5: Grade 1 Nozzle Throat Area Change After the Test (25 bar Chamber Pressure, O/F = 2.3 and 12 Seconds Burn Time)

Erosion characterization tests performed at different fuel type, O/F, P_c , ($\dot{m}_{ox}$), fuel mass, regression rate, thrust and burn time. Working ranges of ECT motor are shown in *Table 2*.

Fuel	DY12 (paraffin-based)
Oxidizer to Fuel Ratio (O/F)	1.5-4.5
Chamber Pressure (P_c)	18-35 bar
Oxidizer Mass Flow ($\dot{m}_{ox}$)	20-100 kg/m^{2}sec
Fuel Mass (M_f)	0.3-0.7 kg
Nozzle Regression Rate ($\dot{r_n}$)	0.02-0.21 cm/sec
Thrust (T)	110-350 N
Burn Time	7 to 20 sec
Combustion Efficiency	%87-95

Table 2: Nozzle Erosion Test Parameters

In *Figure 6*, an example photograph of Erosion Characterization Tests (ECT) is shown.

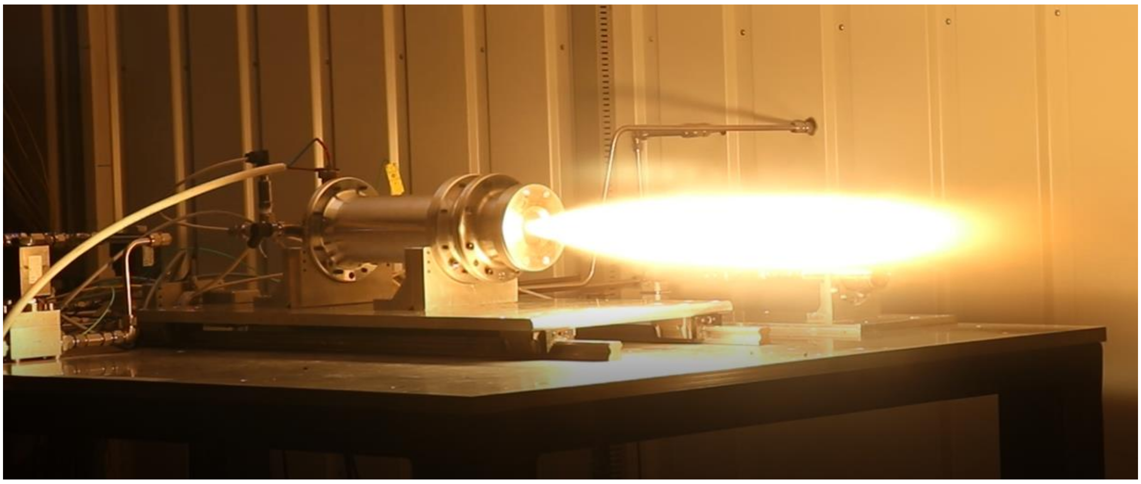

Figure 6: 65 mm GOX and Paraffin-based Hybrid Rocket Test.

In Erosion Characterization Tests different graphite grades and molybdenum were tested. Test results which contain erosion rates and erosion onsets of different nozzle materials will be described in the following section.

III. Results and Discussion

For this study tests were performed by using different materials, different configurations and different formulations. Some tests with a fuel formulation with Aluminum performed to minimize the nozzle erosion in Grade 1. Pressure data which are taken from the tests are very important to find the nozzle erosion onset. Decrease in the tank pressure causes a decrease in chamber pressure as well. However, if there is an extra decrease in the chamber pressure, we can say that erosion starts just before that point. A sample pressure graph is given in *Figure 7*.

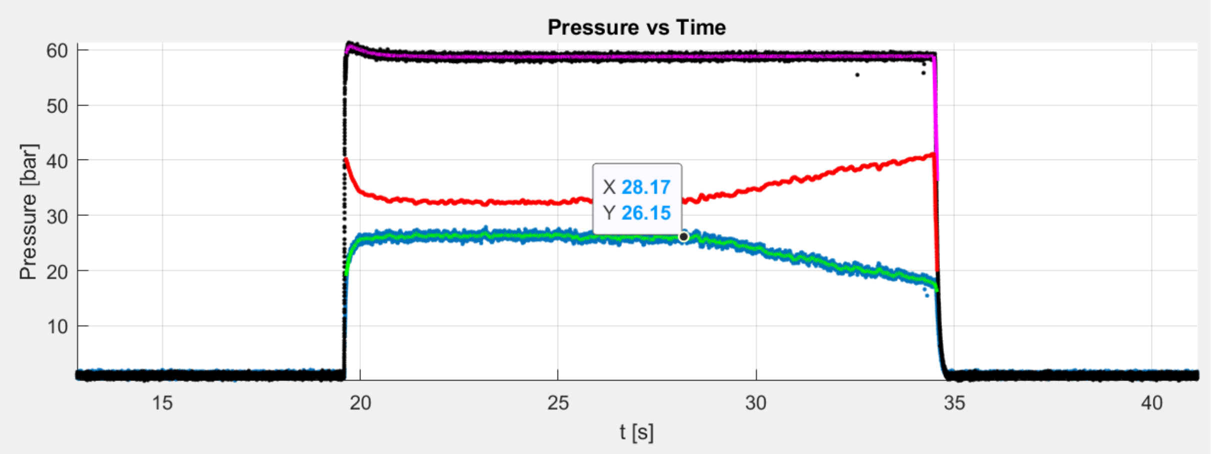

Figure 7: Beginning of the Nozzle Erosion

A. Grade 1 Erosion Rates & Onsets

First of all, graphite grade 1 is used as nozzle material. Specifications of grades are given in *Table 1*. Erosion rate of graphite grade 1 at different O/F ratios are shown in *Figure 8.*

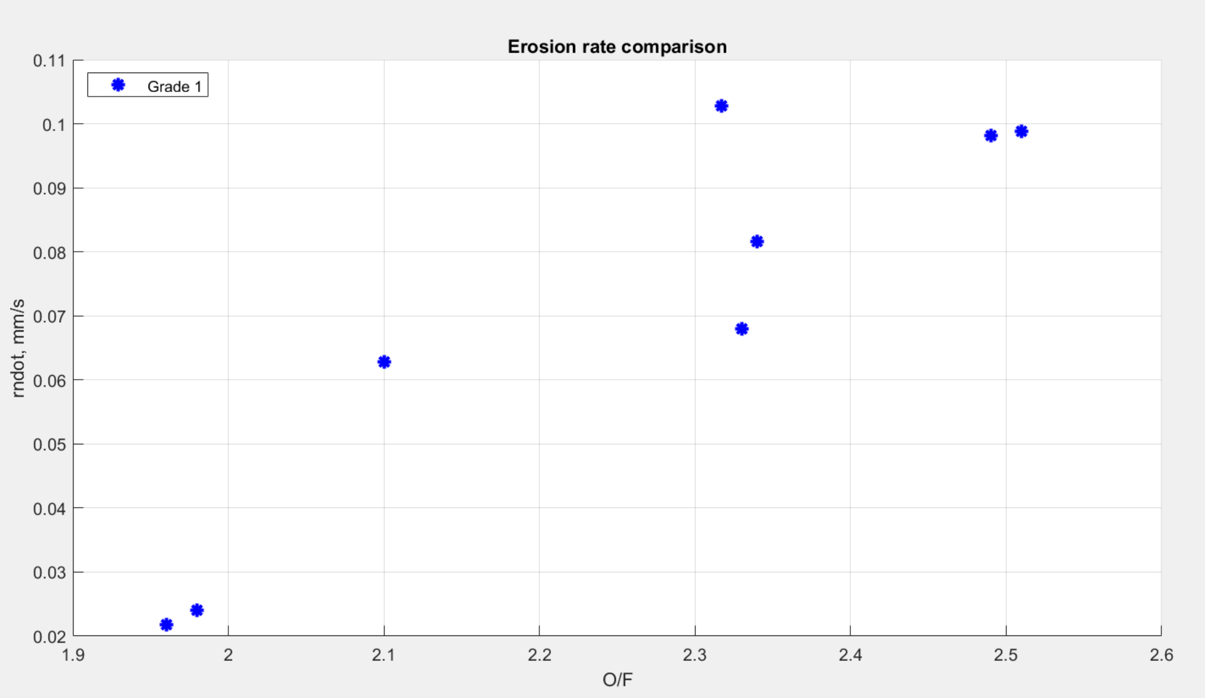

Figure 8: Erosion Rates of Grade 1 at Different O/F Ratios

Nozzle erosion rates increase as O/F ratio increases due to increase in oxidizing agents. This increase can be easily seen in *Figure 8*.

Another important phenomenon is nozzle erosion onset. Erosion does not start at the beginning of the motor firing. It only begins when the temperatures reach at critical values at the throat and chemical reactions start. Thermal conductivity is very important for this reason. Since the material which has high thermal conductivity will transmit the heat more, the surface of the nozzle will not reach at critical values earlier and erosion will start a few seconds later. In addition to this, increase in chamber pressure and O/F ratio reduces the nozzle erosion onset. It means that at higher pressures and oxidizer to fuel ratios, erosion can start earlier due to high mass flux at the throat and high concentrations of oxidizing agents. Reduction of erosion onset of Grade 1 with different O/F ratios is shown in *Figure 9*.

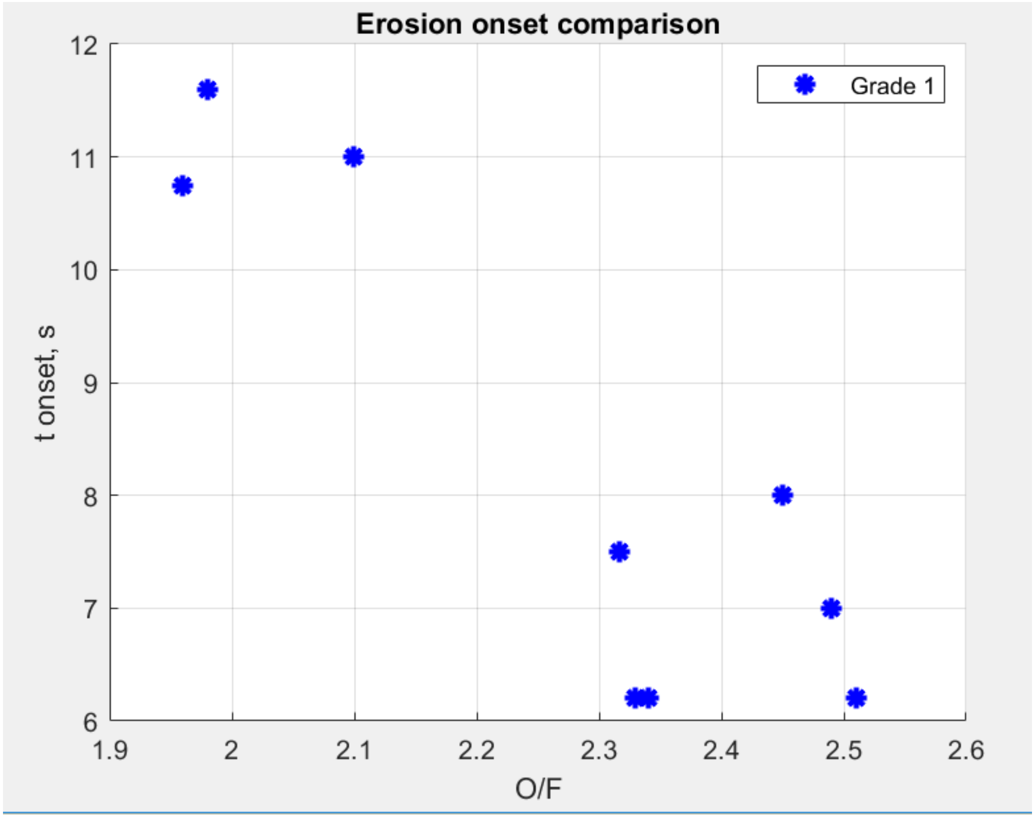

Figure 9: Grade 1 Erosion Onset Variation with O/F Ratio

Fuel with Aluminum only used in the tests which use Grade 1 as nozzle material. It is clearly seen in the figures below that aluminum reduces the erosion rates and increases onsets. Aluminum addition decreased the erosion rate nearly 30% to 45% and also increased nozzle erosion onset by 3 to 5 seconds.

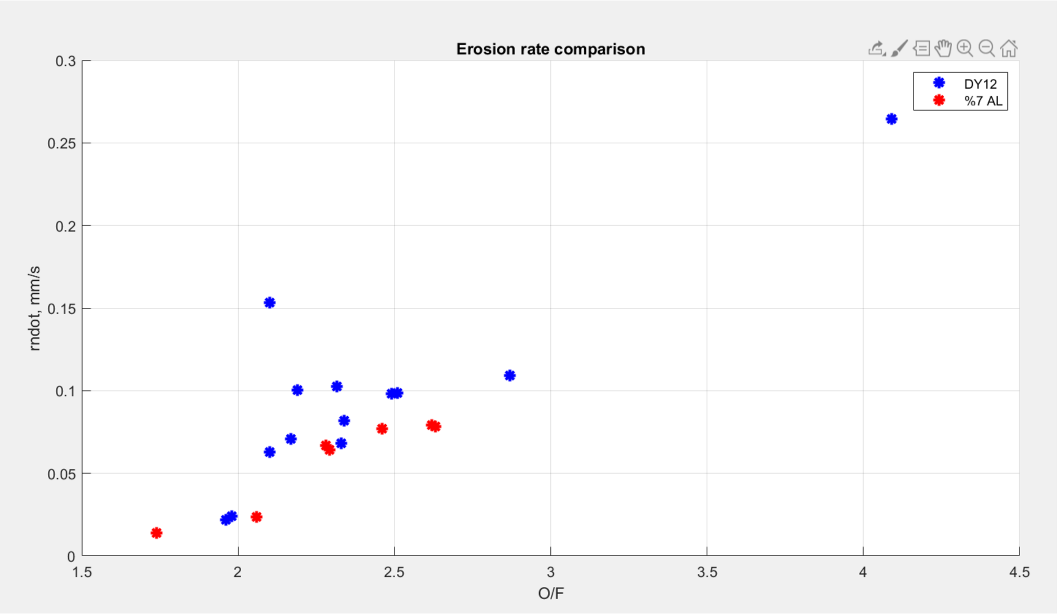

Figure 10: Effect of Aluminum Addition to the DY-12 on the Erosion Rate

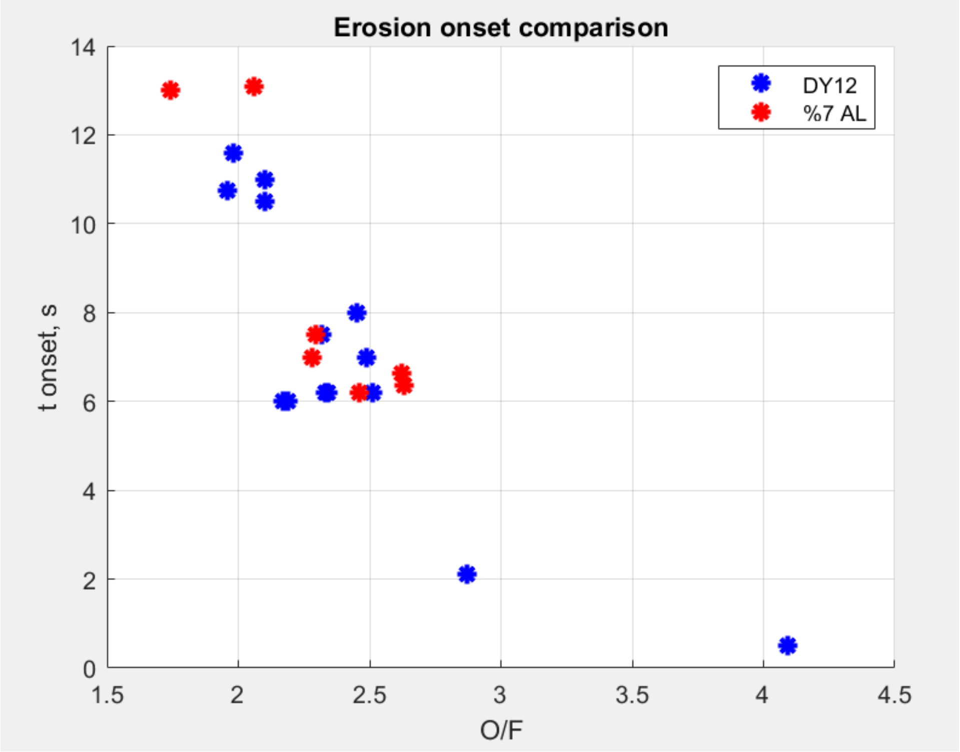

Figure 11: Effect of Aluminum Addition to the DY-12 on the Erosion Onset

Each of the tests have different chamber pressures, so the nozzle erosion rates are corrected for chamber pressure to better compare the results. This correction equation used a linear dependence to chamber pressure because in *Eq. 6* “m” value is generally 1 [5]. Pressure correction took 25 bar as reference pressure.

B. Grade 2 Erosion Rates & Onsets

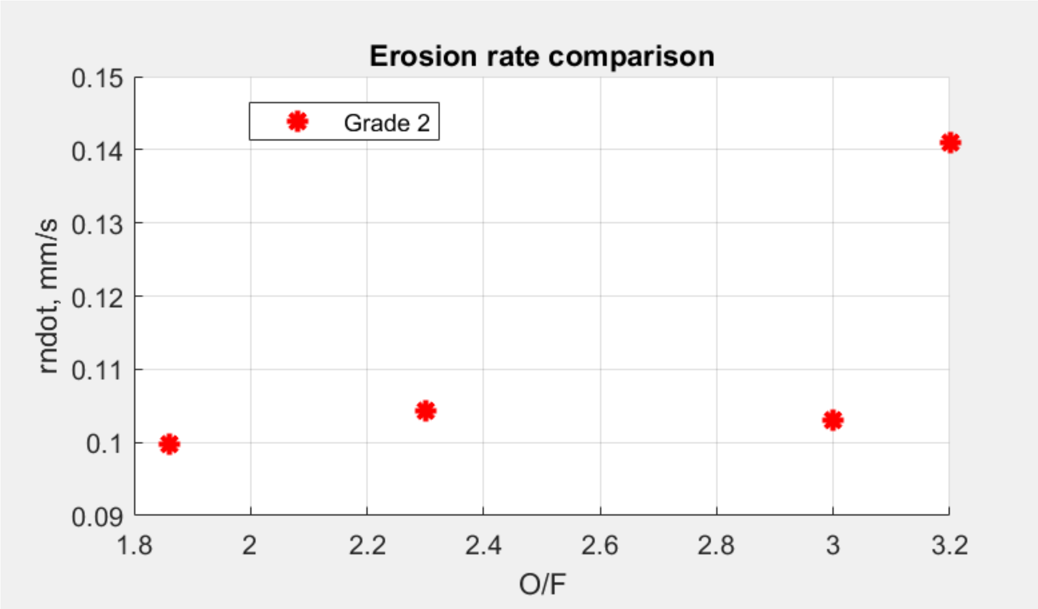

Figure 12: Erosion Rates of Grade 2 at Different O/F Ratios

Nozzle erosion rates increase as O/F ratio increases due to increase in oxidizing agents. This increase can be easily seen in *Figure 12*.

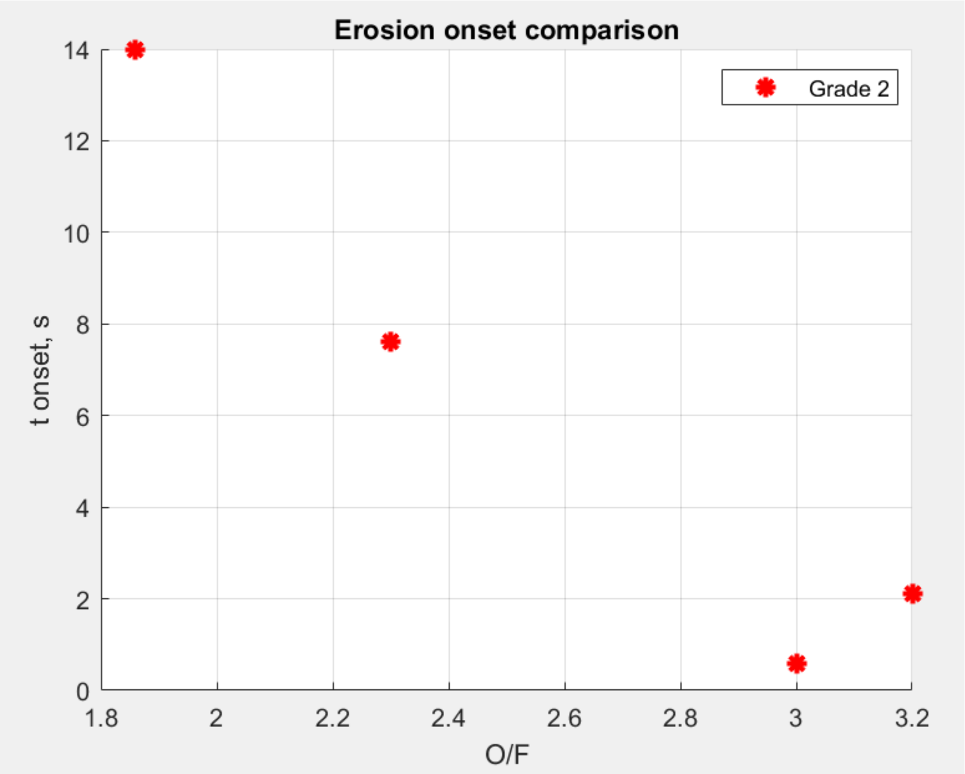

Figure 13: Grade 2 Erosion Onset Variation with O/F Ratio

Reduction of erosion onset of Grade 2 with different O/F ratios is shown in *Figure 13*.

C. Grade 3 Erosion Rates & Onsets

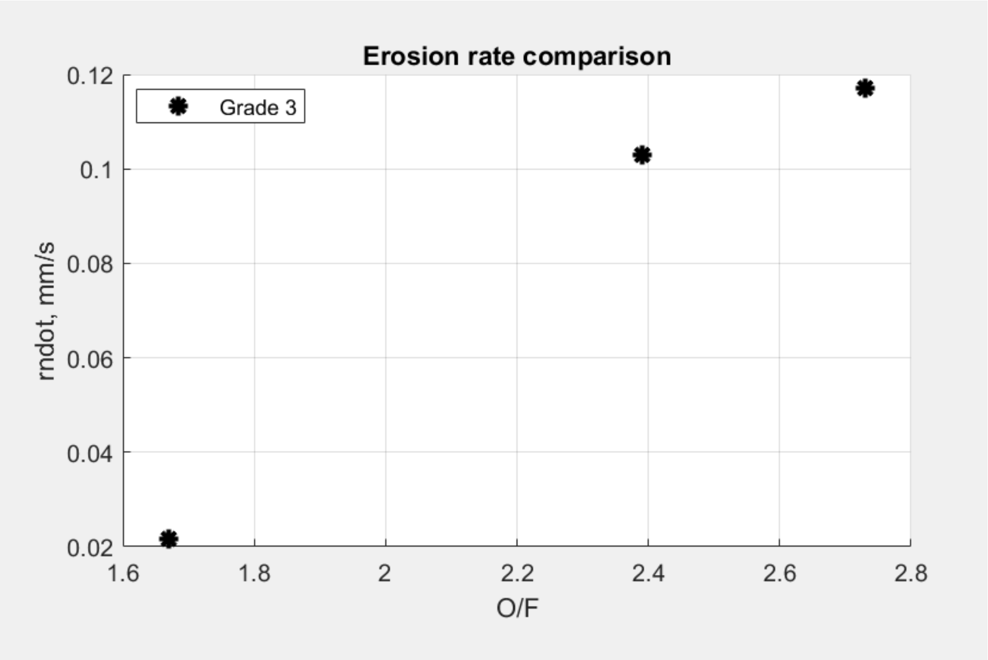

Figure 14: Erosion Rates of Grade 3 at Different O/F Ratios

Nozzle erosion rates increase as O/F ratio increases due to increase in oxidizing agents. This increase can be easily seen in *Figure 14.*

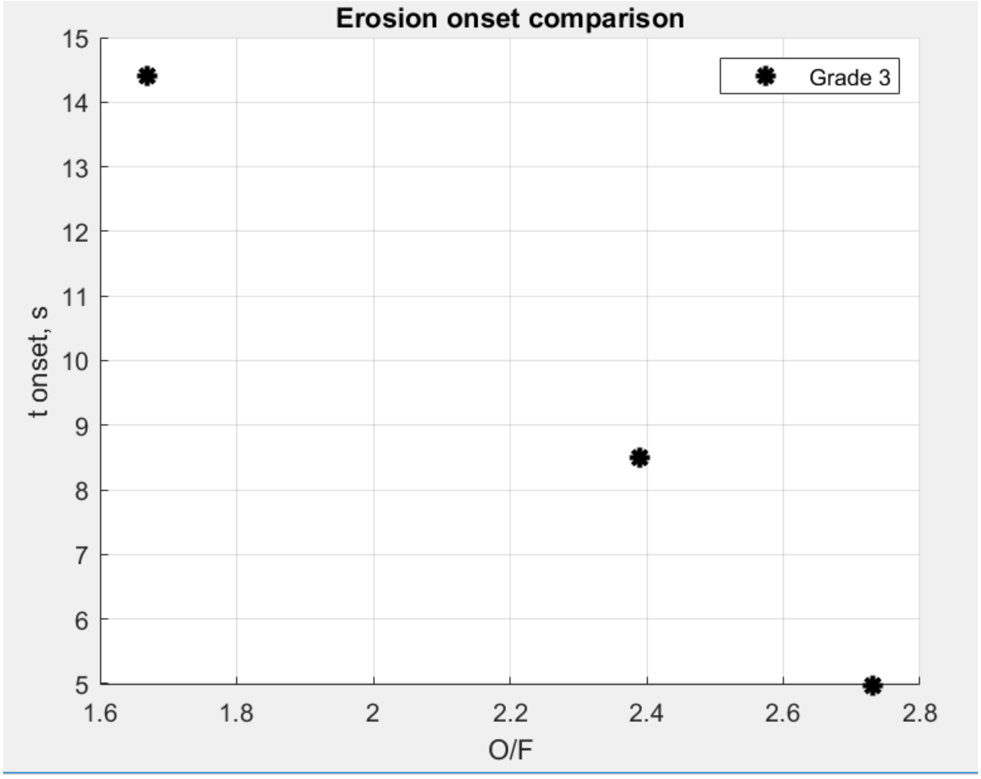

Figure 15: Grade 3 Erosion Onset Variation with O/F Ratio

Reduction of erosion onset of Grade 3 with different O/F ratios is shown in *Figure 15*.

D. Grade 4 Erosion Rates & Onsets

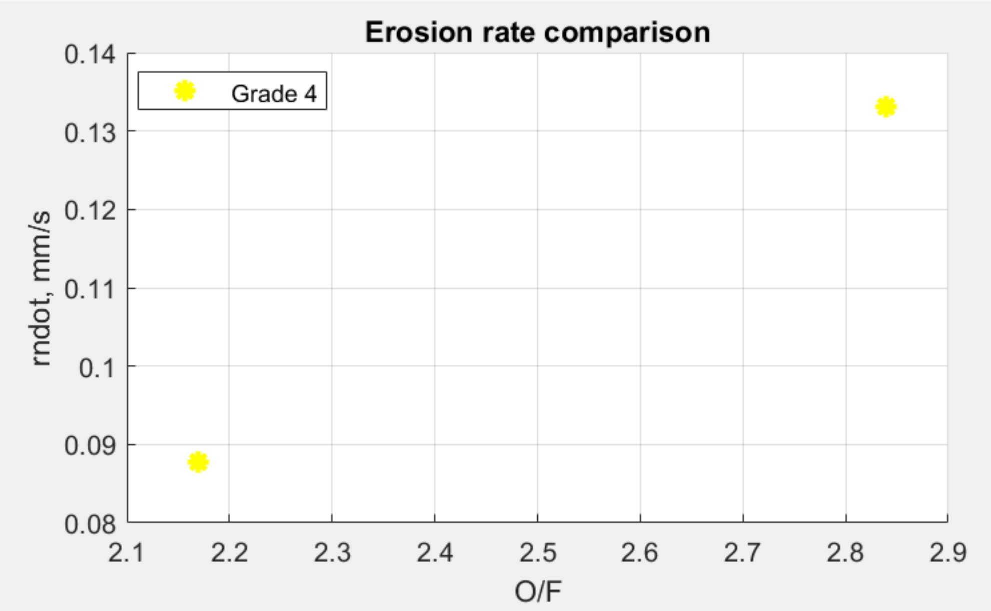

Figure 16: Erosion Rates of Grade 4 at Different O/F Ratios

Nozzle erosion rates increase as O/F ratio increases due to increase in oxidizing agents. This increase can be easily seen in *Figure 16*.

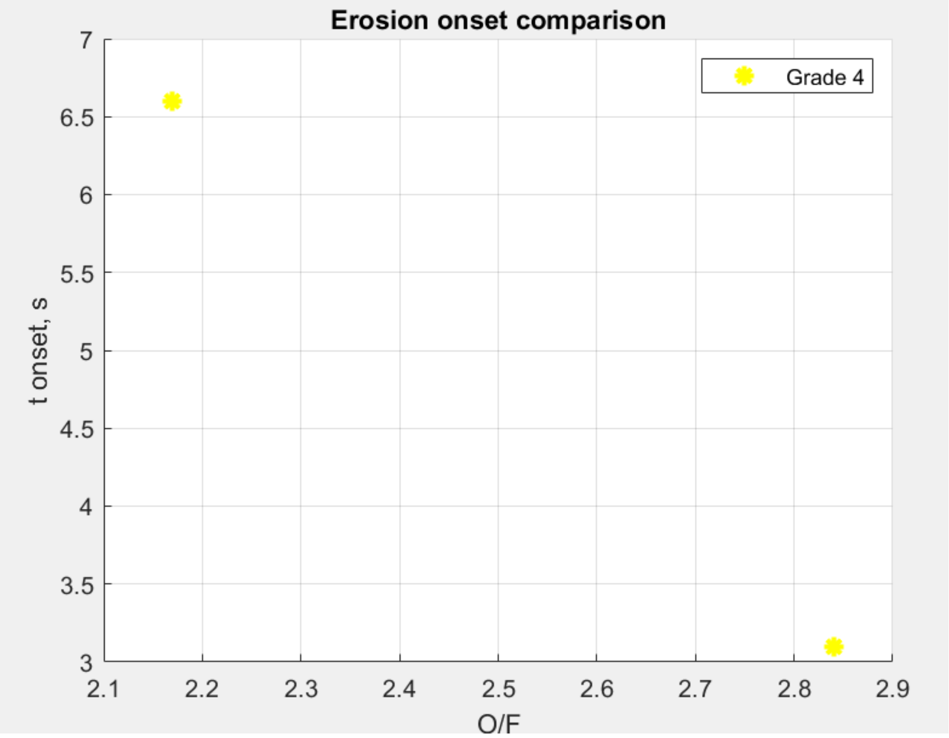

Figure 17: Grade 4 Erosion Onset Variation with O/F Ratio

Reduction of erosion onset of Grade 4 with different O/F ratios is shown in *Figure 17*.

E. Grade 5 Erosion Rates & Onsets

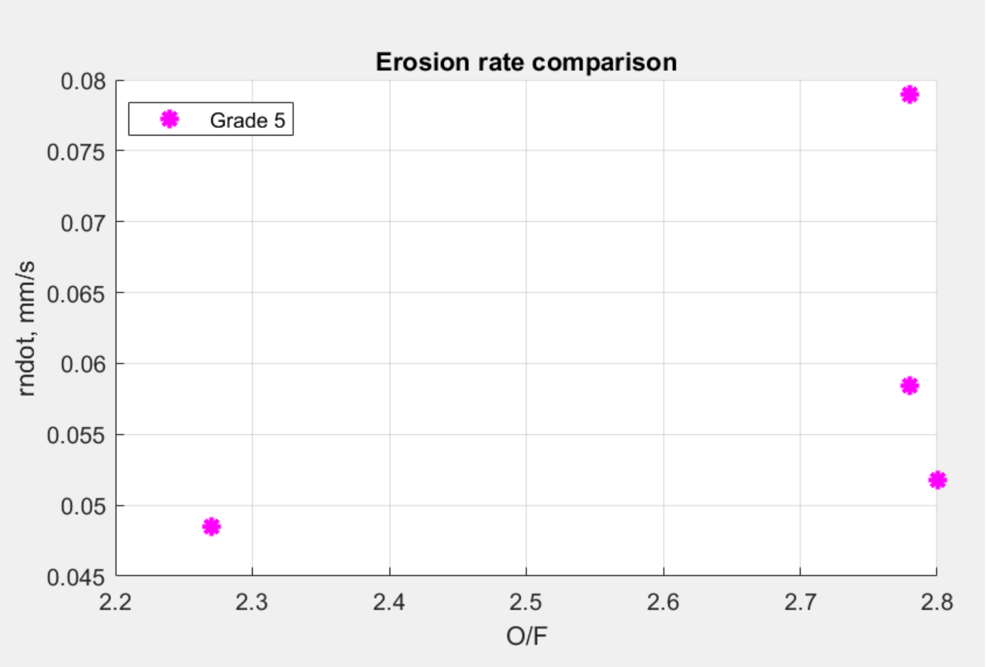

Figure 18: Erosion Rates of Grade 5 at Different O/F Ratios

Nozzle erosion rates increase as O/F ratio increases due to increase in oxidizing agents. This increase can be easily seen in *Figure 18.*

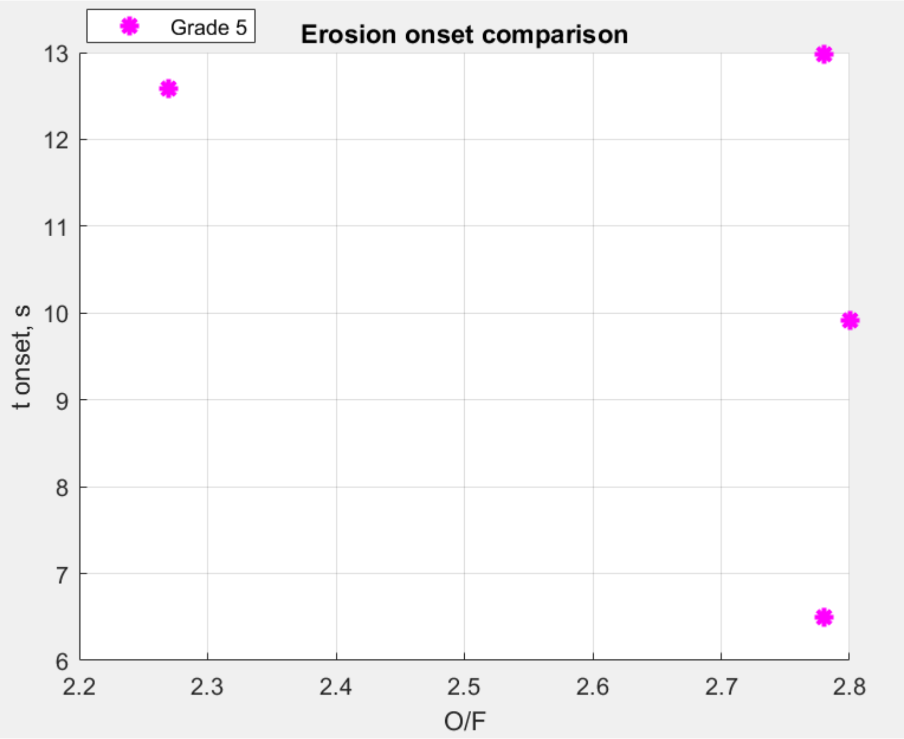

Figure 19: Grade 4 Erosion Onset Variation with O/F Ratio

Erosion onsets of Grade 5 with different O/F ratios are shown in *Figure 19.*

In the results of the grade 5 , there is a different situation from other grades. This is because of production process of the graphite. All parts of the graphites cannot be the same and they can have different porosities if they could not pressed well. If there are some open pores at the surface, flame can easily enter from these pores and erosion can start earlier at that part of the graphite. Therefore, graphite can have different erosion rates and onsets at the same O/F ratios. More tests should be performed to get more accurate data.

F. Molybdenum Erosion Rates & Onsets

Molybdenum is a strength metal that has high melting point nearly 2600 °C. Since it has high melting point and strength it can be used as nozzle material in rocket propulsion systems. Due to its high cost, molybdenum was not used as whole nozzle. Two tests which use molybdenum as nozzle material performed. It was used as nozzle throat insert for the two of the tests.

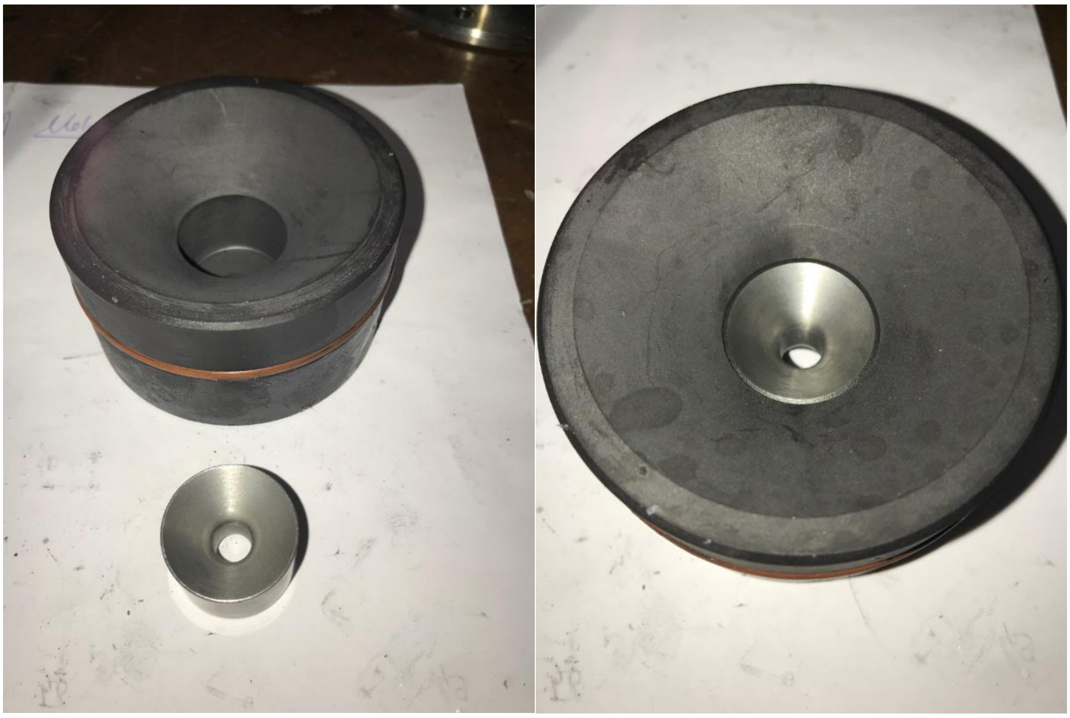

Figure 20: Molybdenum Insert in Graphite Grade 1

Molybdenum test conditions;

25 Bar, O/F = 2.8, 15 seconds of burning.

Nozzle throat diameter of the molybdenum was 7 mm before the test, but it increases 17% and reached 8.2 mm.

After 15 seconds of burning, Molybdenum could not keep its shape. Due to high concentration of oxygen in the oxidizer (GOX), molybdenum eroded. Final shape of the molybdenum is shown in *Figure 21*.

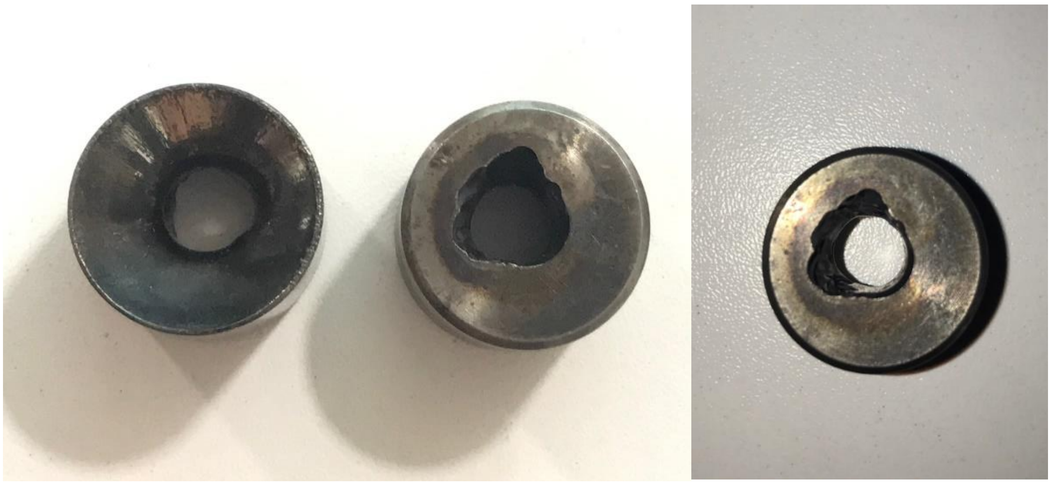

Figure 21: Molybdenum Insert After 15 Seconds of Burning

Pressure, oxidizer mass flow, and thrust profile of one of the molybdenum tests are shown in the figures below.

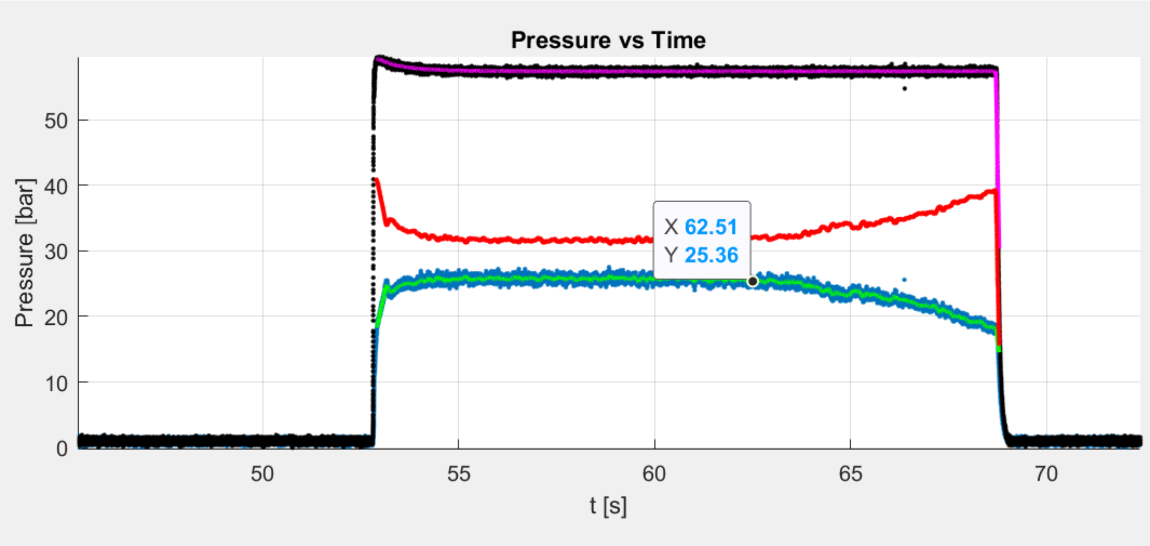

Figure 22: Pressure Data and Erosion Onset for Molybdenum Insert Test

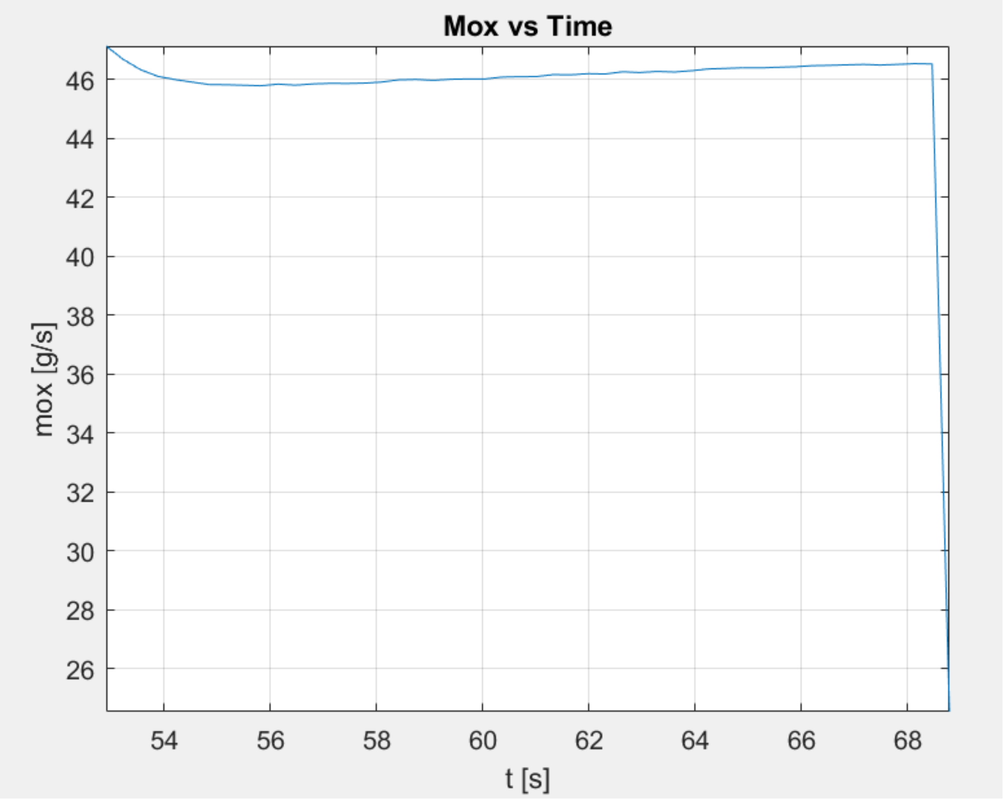

Figure 23: Oxidizer Mass Flow for Molybdenum Insert Test

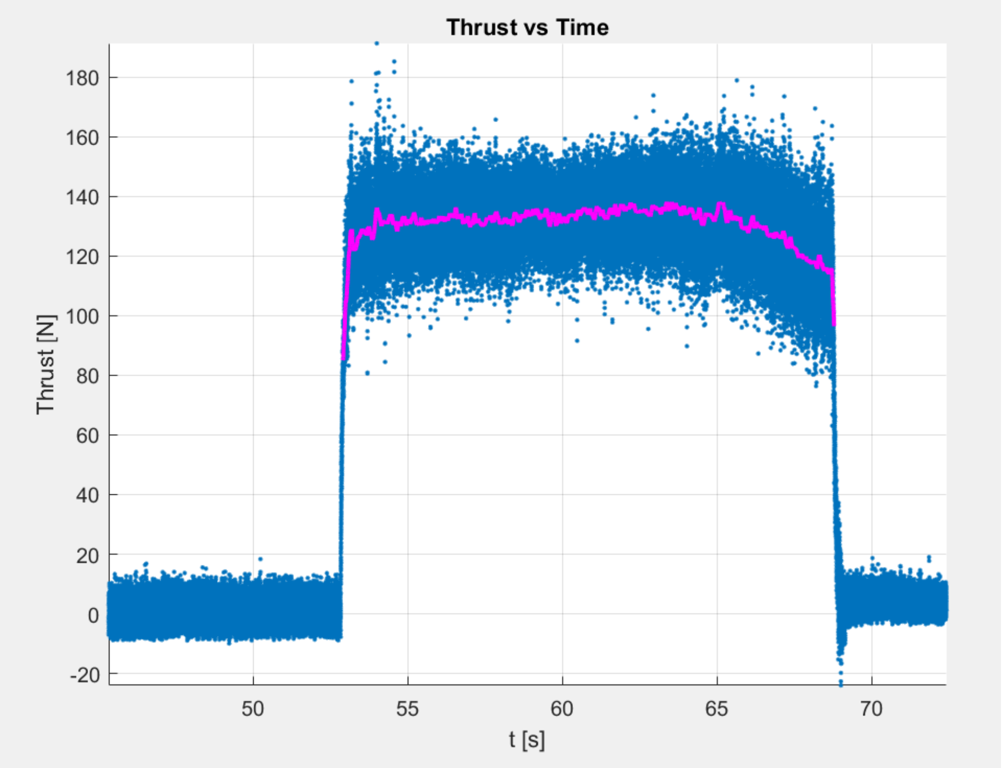

Figure 24: Thrust Profile for Molybdenum Insert Test

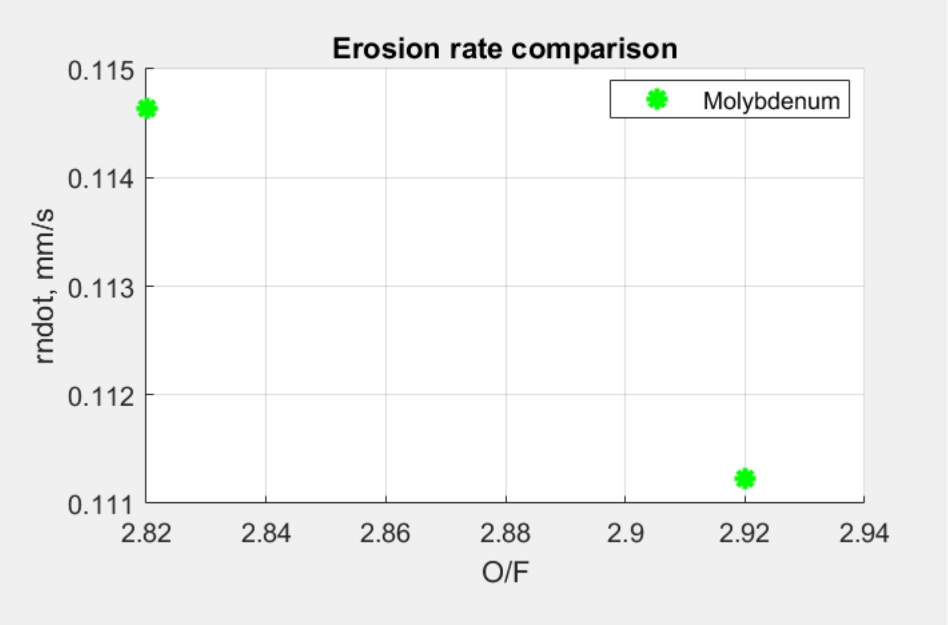

Figure 25: Erosion Rates of Molybdenum at Different O/F Ratios

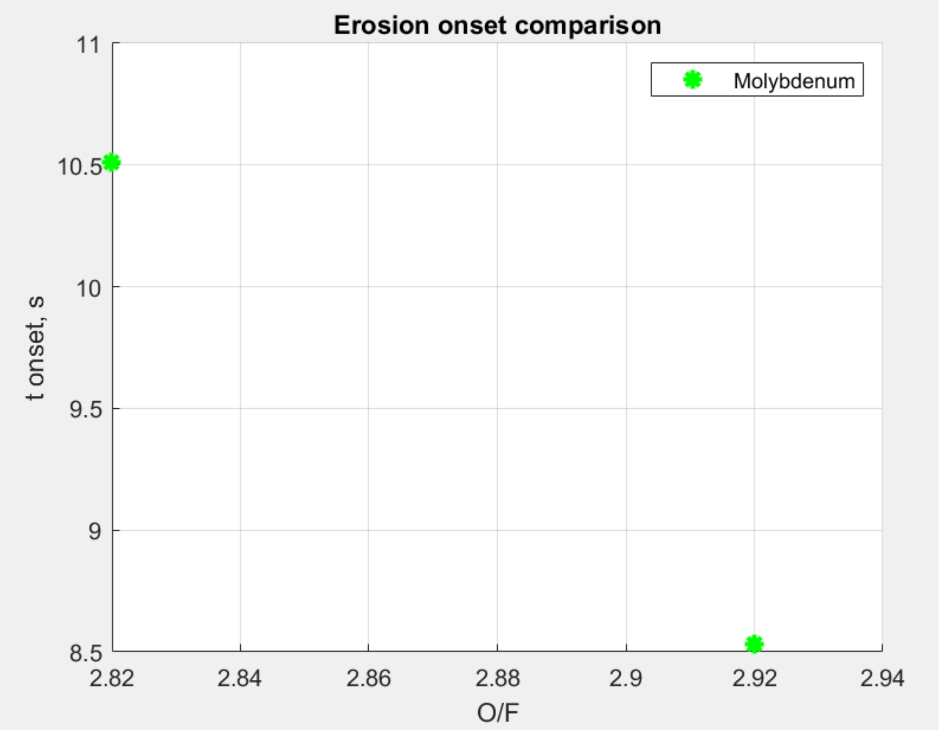

Figure 26: Molybdenum Erosion Onset Variation with O/F Ratio

Erosion rate of molybdenum at higher O/F is expected to be higher, but in this case it is lower. It can be because of combustion process or mechanical structure of molybdenum. More tests should be performed to get more accurate data but one more test cannot be performed due to its high cost.

G. Silica Phenolic Nozzle Development

Ablative materials might be suitable for rocket nozzles.The effective heat of gasification protects the structure of the nozzle from heat. Silica phenolic is an ablative material that can be used for high temperatures.

A sample nozzle was made from Silica Phenolic fibers and chopped fibers. The test failed because Silica Phenolic nozzle was split into two parts. For this reason, erosion rate of the nozzle could not be measured. This situation shows us the importance of the production process. Development of Silica Phenolic nozzle continues.

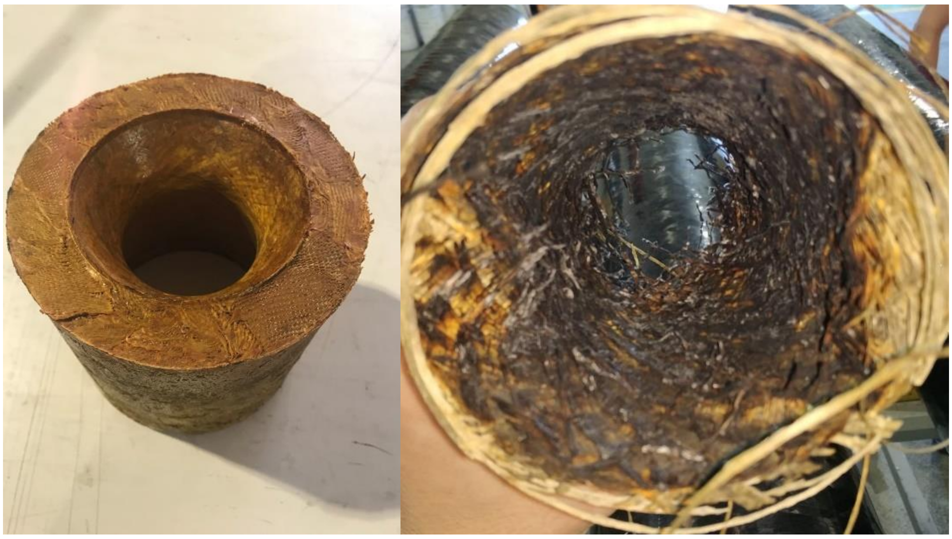

Figure 27: Initial & After Silica Phenolic Nozzle

If we compare all of the results, Grade 5 is the best of all graphite grades and molybdenum. Data of all the tests are shown in the figure below.

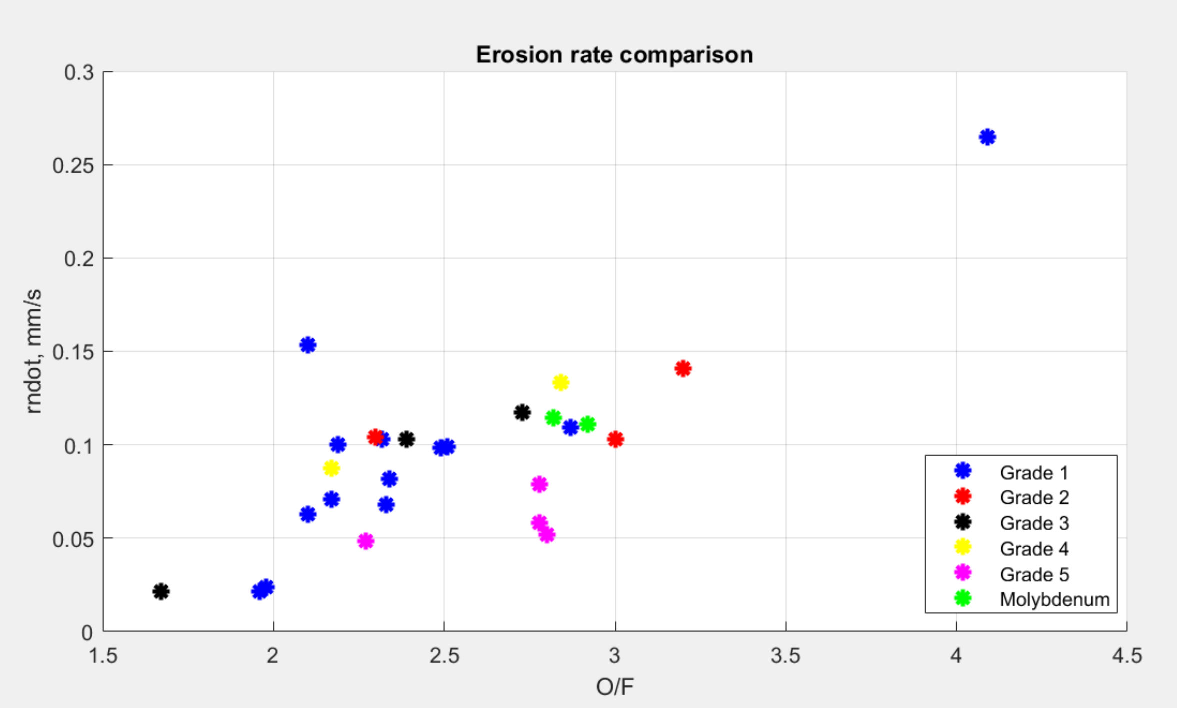

Figure 28 : Erosion Rates of Different Materials at Different O/F Ratios

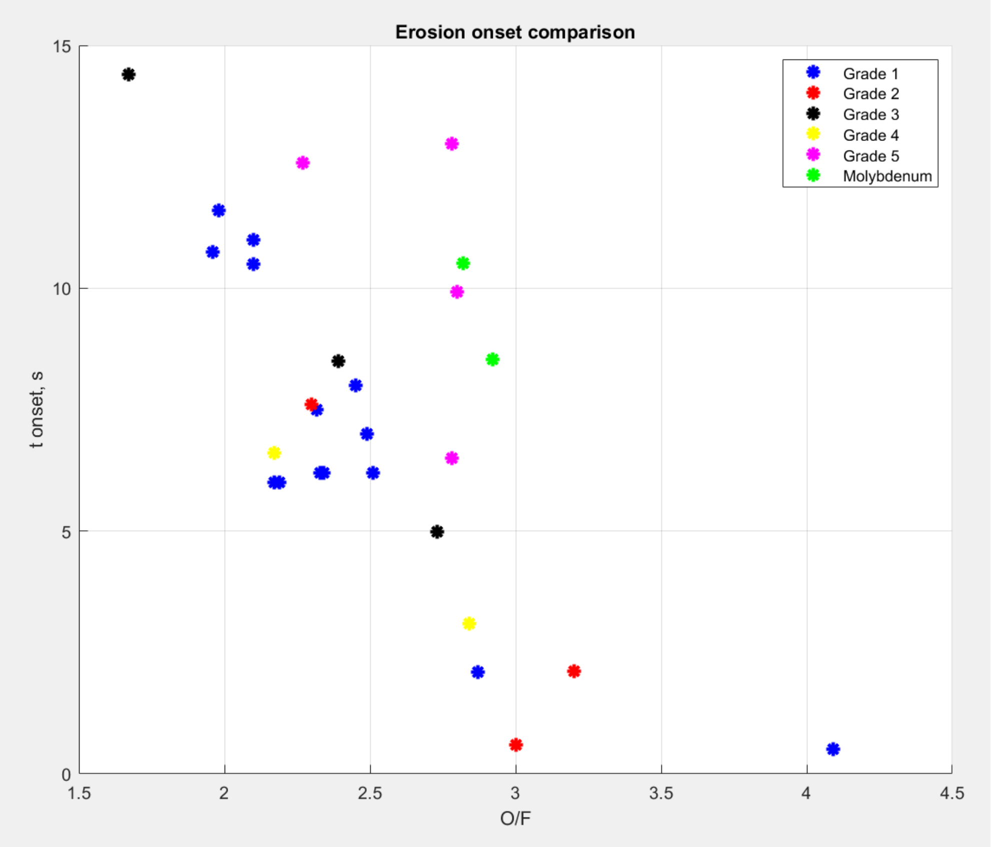

Figure 29: Erosion Onsets of Different Materials at Different O/F Ratios

Erosion onset of the Grade 5 is higher than the others at the same O/F ratios and also its erosion rate is lower than the erosion rates of the others at the same O/F ratios. Therefore, we saw the benefit of smaller grain size and lower ash content.

Nozzle test results are given at the table below.

Grade	Burn Time (Sec)	Chamber Pressure (bar)	O/F Ratio	Initial Throat Diameter (mm)	Final Throat Diameter (mm)	Erosion Onset (Sec)	Erosion Rate (mm/sec)
Grade 1	7.92	21	2.45	7.51	7.52	8	0
Grade 1	19.94	18	2.3	7.51	9.35	7.5	0.0740
Grade 1	11.7	30	1.96	7.95	8	10.75	0.0263
Grade 1	16.79	32	1.98	7.53	7.85	11.6	0.0308
Grade 1	11.64	23	2.51	7.5	8.55	6.2	0.0920
Grade 1	14.86	26	2.1	7.5	8	11	0.0650
Grade 1	16.98	23	2.49	6.98	8.8	7	0.0910
Grade 1	11.58	30	2.33	7.46	8.36	6.2	0.0834
Grade 1	11.87	20	4.09	7.48	12.45	0.5	0.2184
Grade 1	14.78	26	2.09	7.03	8.34	7.3	0.0876

Table 3: Grade 1 Test Results

Grade	Burn Time (Sec)	Chamber Pressure (bar)	O/F Ratio	Initial Throat Diameter (mm)	Final Throat Diameter (mm)	Erosion Onset (Sec)	Erosion Rate (mm/sec)
Grade 2	14.79	16	3.2	7.00	9.32	2.11	0.0916
Grade 2	14.74	20	3	7.00	9.34	0.6	0.0830
Grade 2	14.9	25	2.3	7.50	9.02	7.6	0.1040
Grade 2	14.7	25	1.86	8.01	8.15	14	0.100

Table 4: Grade 2 Test Results

Grade	Burn Time (Sec)	Chamber Pressure (bar)	O/F Ratio	Initial Throat Diameter (mm)	Final Throat Diameter (mm)	Erosion Onset (Sec)	Erosion Rate (mm/sec)
Grade 3	15.86	20	2.73	7.00	8.97	8	0.0906
Grade 3	14.8	26	2.39	7.50	8.86	7.5	0.1083
Grade 3	14.75	25	1.67	8.01	8.025	10.75	0.0214

Table 5: Grade 3 Test Results

Grade	Burn Time (Sec)	Chamber Pressure (bar)	O/F Ratio	Initial Throat Diameter (mm)	Final Throat Diameter (mm)	Erosion Onset (Sec)	Erosion Rate (mm/sec)
Grade 4	15.9	18	2.84	7.00	9.48	3.1	0.097
Grade 4	14.8	24	2.17	7.50	8.9	6.6	0.0856

Table 6: Grade 4 Test Results

Grade	Burn Time (Sec)	Chamber Pressure (bar)	O/F Ratio	Initial Throat Diameter (mm)	Final Throat Diameter (mm)	Erosion Onset (Sec)	Erosion Rate (mm/sec)
Grade 5	15.89	24	2.80	7.00	7.59	9.92	0.0498
Grade 5	14.84	26	2.27	7.50	7.73	12.59	0.0511
Grade 5	15.9	23	2.78	7.00	8.01	6.5	0.0537
Grade 5	16.88	24	2.78	6.99	7.58	12.98	0.0756

Table 7: Grade 5 Test Results

Grade	**Burn Time (Sec)**	**Chamber Pressure (bar)**	**O/F Ratio**	**Initial Throat Diameter (mm)**	**Final Throat Diameter (mm)**	**Erosion Onset (Sec)**	**Erosion Rate (mm/sec)**
Molybdenum 1	14.93	24	2.92	6.99	8.375	8.53	0.1082
Molybdenum 2	15.88	24	2.82	6.99	8.19	10.51	0.1117

Table 8: Molybdenum Test Results

IV. Conclusion

This study shows that operating pressure, O/F ratio, fuel formulation and nozzle material play very important role in nozzle erosion rate. Operating at lower O/F ratios and lower chamber pressures can minimize the erosion rate. In addition, a fuel formulation with Al also gives better erosion rates. Material selection is very important suitable material should be chosen for the propulsion system. In hybrid rocket motors, graphite, metals, and ceramics can be good choice. Among the tested materials, the best graphite is determined as Grade 5 which has the lowest grain size. In future, more tests will be performed and Silica Phenolic and Silicon Carbide nozzles will be tested.

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